Moving-Coil Telephone Receivers and Microphones *

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A description is given of a moving-coil head receiver and a microphone designed particularly for high quality transmission. The instruments have a substantially uniform response from 40 to 10,000 c.p.s. This uniformity of response has been obtained, without sacrifice of sensitivity, by the use of light moving parts and the association of special types of acoustic networks with the diaphragm. In practical use the microphone has a sensitivity about 10 db higher than that of the Western Electric 394 Condenser Microphone.

MOVING-COIL loud speakers are now extensively used in high quality radio-receiving sets and in talking motion picture equipment. The chief advantages of the moving coil over the moving armature driving mechanism are the absence of a static force, constancy of force-factor and electrical impedance throughout a wide frequency range, and freedom from non-linear distortion over a wide amplitude range. Because of these advantages it seems obvious that the moving coil structure can also be used profitably in head receivers and microphones where high quality is of prime importance. It has therefore been adopted in the instruments to be described, although some of the principles here formulated can conceivably be applied also to instruments with moving armatures. This paper is concerned primarily with the general principles of design. The more practical phases of the commercial design and construction of the microphone are discussed in a paper by W. C. Jones and L. W. Giles.[1]

The moving system of a head receiver must, in general, satisfy distinctly different requirements from that of a microphone. In the actual use of the receiver a small enclosed cavity is formed between the ear and the diaphragm. If there is to be no distortion the pressure developed within this enclosure per unit of current in the receiving coil should be independent of frequency, constancy of impedance of the coil being assumed. The pressure depends not only upon the amplitude of vibration of the diaphragm, but also upon the acoustic impedance of the cavity formed by the ear and the receiver. This impedance is such, if the cavity is entirely enclosed, that at low frequencies the pressures will be very nearly proportional to the displacement of the diaphragm. At higher frequencies it is of uncertain value and varies from ear to ear, but it appears, from unpublished

* Jour. Acous. Soc. Amer., July, 1931.

[1] "Moving Coil Microphone for High Quality Sound Reproduction." Presented at May 1931 meeting of Soc. of Motion Picture Engineers, Hollywood, California.

data obtained by L. J. Sivian on a large number of ears, that constant amplitude of motion of the diaphragm per unit current throughout the frequency range is on the average the best condition to strive for in the design of a high quality receiver. We shall therefore assume that at any frequency the amplitude of motion of the diaphragm per unit current is a correct measure of the response of the receiver. It will be assumed also that the impedance of the cavity is without effect on the displacement of the diaphragm. For the receivers to be considered this assumption introduces but little error, although the effect is not negligible in general.

The voltage generated by a moving coil in a magnetic field is proportional to the velocity; therefore, the diaphragm of a uniformly sensitive microphone with a rigidly attached coil should have, at all frequencies, the same velocity per unit of pressure in the actuating sound wave. Expressed in another way, if the diaphragm has a constant effective area, the mechanical impedance (force per unit velocity) of a microphone diaphragm should be the same at all frequencies, whereas that of the receiver should be inversely proportional to the frequency. The receiver and the microphone to be described are quite similar in design and construction, but their dynamical constants differ so as to approach these conditions of impedance.

If a receiver or microphone is constructed with a diaphragm having a single degree of freedom, the operating conditions of the diaphragm can be represented by the circuit diagram shown in Fig. 1, where m_0

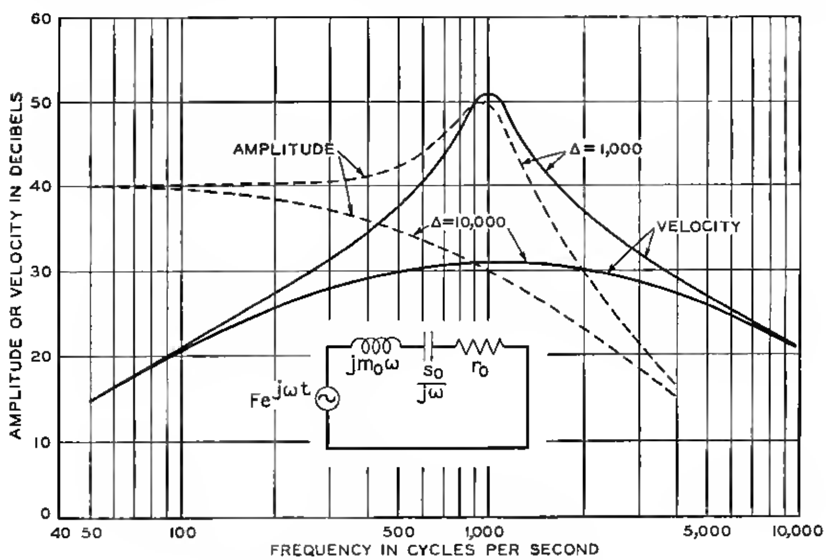


Fig. 1—Response of a simple resonant system.

is the effective mass, s_0 the stiffness, r_0, the mechanical resistance of the diaphragm, and $Fe^{j\omega t}$ the alternating force acting upon the diaphragm. The absolute value of the velocity of the diaphragm is given by

$$v = \frac{F}{m\left[4\Delta^2 + \left(\frac{\omega^2 - \omega_0{}^2}{\omega}\right)^2\right]^{1/2}}$$

and the amplitude by v/ω where $\Delta = \frac{r_0}{2m_0}$, the damping constant, and $\omega_0 = \sqrt{\frac{s_0}{m_0}} = 2\Pi \times$ resonant frequency. The velocities and amplitudes for a constant force and for two different values of Δ, calculated from these expressions, are graphically represented in Fig. 1. Both the amplitude and velocity curves show wide variations in response with frequency. They indicate that for small variations in amplitude the resonant frequency must be near the upper limit of the frequencies to be transmitted and for small variations in velocity the damping constant must be high. But instruments designed on this basis would be relatively insensitive even if such conditions could be met readily in their construction.

In the design of electrical networks for the transmission of wide frequency bands the end is attained by the combination of more than one resonant circuit. We can advantageously resort to a similar expedient in a mechanical system by the use of a structure more complicated than one having a single degree of freedom. The diaphragm may be coupled to another mechanical or acoustical network of the proper type so as to give us the desired uniformity of response. The circuit diagram of one such mechanical network is shown in Fig. 2,

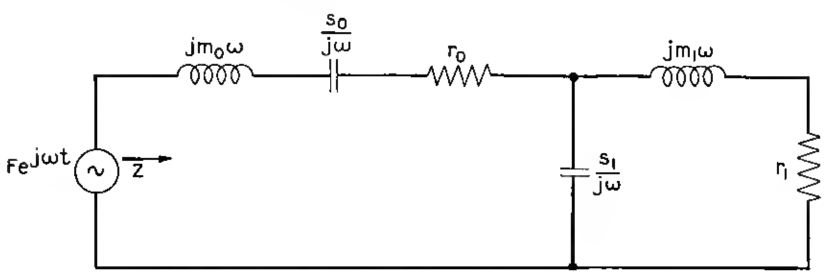


Fig. 2—Circuit diagram for receiver or microphone.

where s_1 is the stiffness, m_1 the mass, and r_1 the resistance of the elements of the coupled network. The construction of a mechanical system represented by this diagram is brought out in detail in the

discussion of the mechanical design of the instruments which is to follow. The actual values of the constants are to be so chosen, if possible, that the mechanical impedance, z, of the whole network is constant with frequency in the case of the microphone and inversely proportional to the frequency for the receiver. The absolute value of this impedance, z, is $\sqrt{r^2 + x^2}$ where

$$\left.\begin{aligned} r &= \frac{s_1^2 r_1}{r_1^2\omega^2 + m_1^2(\omega_1^2 - \omega^2)^2} + r_0, \\ x &= \frac{s_1\omega[m_1^2(\omega_1^2 - \omega^2) - r_1^2]}{r_1^2\omega^2 + m_1^2(\omega_1^2 - \omega^2)^2} + m_0\omega - \frac{s_0}{\omega}, \\ \omega_1^2 &= \frac{s}{m_1}. \end{aligned}\right\} \qquad (1)$$

The Electrodynamic Receiver

If the mechanical system of the receiver can be represented by the circuit diagram shown in Fig. 2, then, as the amplitude per unit force is a measure of the receiver response, we may calculate the product of frequency and impedance and so get a response-frequency characteristic for any specified set of values of the constants. Such characteristics are graphically shown in Fig. 3 for several sets of values. Curves

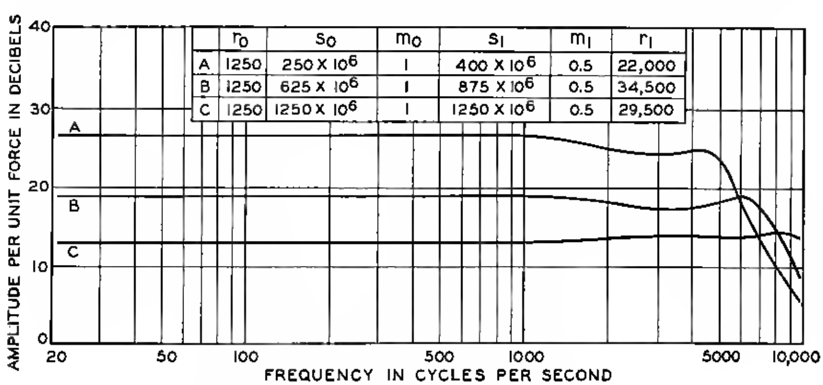


Fig. 3—Theoretical response curves of moving coil receiver.

of identical character but of different level would, of course, be obtained if the magnitude of each of the corresponding impedance elements were changed in the same proportion. It is seen from these curves that, theoretically at least, it is possible to obtain a uniform response over a wide frequency range. Curve C, for example, shows a variation of less than 1.5 db for frequencies up to 10,000 c.p.s. As might be expected, the wider the frequency range of uniform response

the lower the sensitivity. In fact, it can be shown from equations (1) that, if the scale of frequencies is changed by a factor, k, the relative values of the ordinates will be unchanged provided r_1 and r_0 are multiplied by k, and s_1 and s_0, by k^2, but that the amplitude per unit of force at corresponding points on the curve will be changed by a factor equal to $1/k^2$. A receiver transmitting up to 10,000 c.p.s. will thus be 12 db less efficient than one transmitting equally well up to only 5000 c.p.s., the same mass and size of diaphragm being assumed.

Construction of the Receiver

The general construction of a receiver embodying the above principles is shown in Fig. 4. The central portion of the diaphragm is

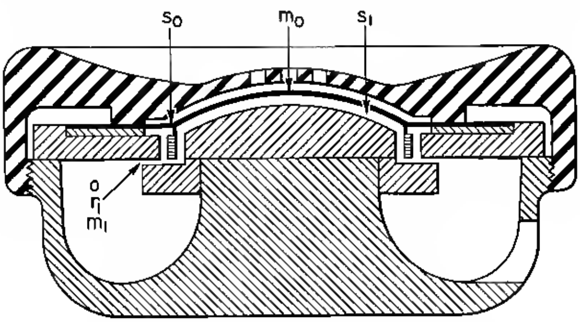


Fig. 4—Moving coil head receiver.

drawn into the form of a spherical dome to increase its rigidity. The receiving coil is of the self-supporting ribbon type, the construction of which has been described previously.[2] It is rigidly attached to the base of the domed portion of the diaphragm. The radial magnetic field is derived from a permanent magnet. The mass of the diaphragm plus that of the coil corresponds to m_0 in Fig. 2, the stiffness of the diaphragm to s_0 and the mechanical resistance to r_0.

A small volume of air is completely enclosed between the diaphragm and pole-pieces save for a narrow slit at O. The acoustic resistance [3] of a slit of this character is equal to $\frac{12\mu l}{d^3 w}$ and the reactance, $j\frac{6}{5}\frac{\rho l}{wd}\omega$, where μ is the viscosity of air, l the radial length, d the width, w the annular length of the slit and ρ the density of air. If the air in the chamber were incompressible a mechanical resistance and reactance would be imposed on the diaphragm by virtue of the air flow through the slit, their respective values would be equal to the acoustic resistance and

[2] *Bell System Technical Journal*, Vol. VII, p. 144, 1928.

[3] Lamb "Hydrodynamics," 4th ed., p. 577.

the acoustic reactance of the slit multiplied by the square of the effective area of the diaphragm. These quantities are represented by r_1 and $j\,m_1\omega$ in Fig. 2. If the slit, O, were closed the stiffness imposed by the air chamber on the diaphragm would be equal to $\frac{\gamma A^2 10^6}{V}$, where A is the effective area of the diaphragm, V the volume of air in the enclosure and γ the ratio of specific heats of air. This is the stiffness represented by s_1 in Fig. 2.

In adjusting the width of the slit to the desired value its resistance was measured experimentally. For this purpose a steady stream of air at low velocity was passed in series through the slit and a capillary tube. The pressure drop through the tube and that through the resistance was then measured with a manometer. The ratio of these values is under this condition equal to the ratio of the resistance of the tube to that of the slit. The resistance of the tube had previously been determined as a function of the pressure difference between its two ends when air was passed through it at a known steady rate. The apparatus is diagrammatically shown in Fig. 5.

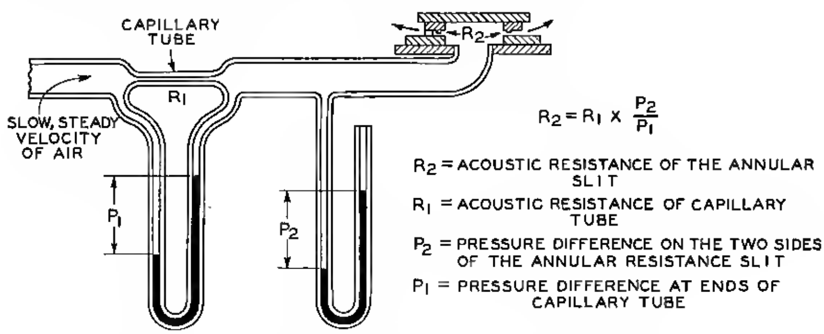


Fig. 5—Method used to measure acoustic resistance.

The response-frequency characteristic of the receiver was determined experimentally. For these measurements it was placed over a calibrated condenser microphone so as to form a 15 c.c. enclosure between the receiver and the microphone diaphragms. This space was filled with hydrogen to avoid acoustic resonance at the higher frequencies. While current from a vacuum tube oscillator was passed through the receiver coil, the voltage generated by the microphone, as well as the receiver current, was measured. From these values, the calibration curve of the microphone and the volume of the enclosure, the amplitude of the receiver diaphragm per unit current is readily determined. Values so obtained, expressed in db, are plotted in Fig. 6. In the

same figure are given values of the response as determined by computation of the mechanical impedance from the constants of the receiver. The ordinates were so adjusted arbitrarily as to bring the computed and observed values into coincidence at the lower frequencies. There is a general agreement between the computed and ob-

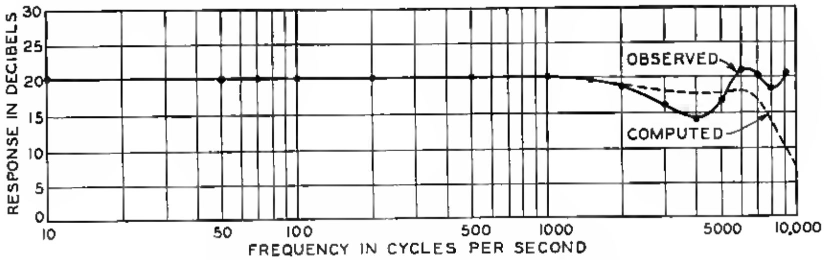


Fig. 6—Response of moving coil receiver.

served curves, yet the variations are larger than can be accounted for on the basis of experimental errors. It is probable that the quantities used in the calculations are not strictly constant up to the higher frequencies, where the diameter of the diaphragm becomes comparable to the wave-length of sound. However, except for a depression in the neighborhood of 4000 c.p.s., the measured is better than the computed characteristic.

A receiver of this general character was supplied for the Master Reference Systems for Telephone Transmission [4] in Europe and in America where it has been in service since 1928.

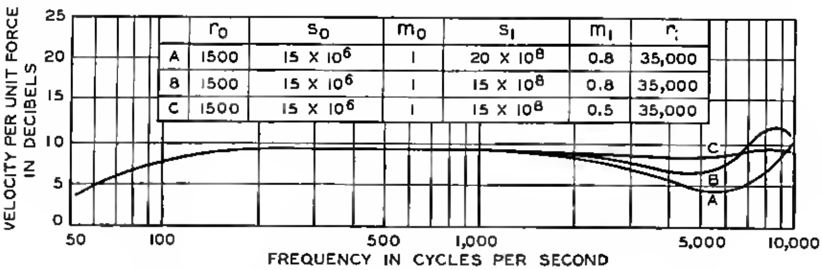
The Moving Coil Microphone

It has been pointed out that in an electrodynamic microphone of high quality the diaphragm with a rigidly attached coil should have the same velocity per unit of force throughout the frequency range. If the dynamical system of the microphone is represented by the mechanical circuit of Fig. 2, this condition requires that the constants of the various elements of this circuit be so chosen that the magnitude of the impedance, z, is the same at all frequencies. It is evident that these values will differ materially from those of the high quality receiver.

In Fig. 7 the impedance expressed in db as determined by equations (1) is shown as a function of frequency for several sets of values of the constants of the impedance elements. They show how, by the proper choice of these values, a uniform response may be obtained over a

[4] "Master Reference System for Telephone Transmission," by W. H. Martin and C. H. G. Gray, *Bell Sys. Tech. Jour.*, July, 1927.

wide frequency range. Curve C, for instance, shows a variation of less than 1.5 db from 200 to 10,000 c.p.s. It may be shown from equations (1) that if the scale of frequencies is changed by a factor k the form of the response curve will remain unchanged, provided r_1 and r_0 are multiplied by k, and s_1 and s_0, by k^2; but the absolute value of the velocity per unit force will be changed by the factor $1/k$ at all points on the curve. Thus, under these conditions, if the last value of the abscissæ in Fig. 7 is designated as 5000 instead of 10,000 c.p.s.,



	r_0	s_0	m_0	s_1	m_1	r_1
A	1500	15×10^6	1	20×10^8	0.8	35,000
B	1500	15×10^6	1	15×10^8	0.8	35,000
C	1500	15×10^6	1	15×10^8	0.5	35,000

Fig. 7—Theoretical response curves of moving coil microphone.

then $k = 0.5$ and the curves will remain unchanged in form but the ordinates will be raised 6 db. The form of any of the curves of Fig. 7 will, of course, not be changed if all the corresponding constants are changed proportionally, although the absolute value of the velocity per unit of force will vary inversely with the magnitude of these constants.

At zero frequency the velocity of the diaphragm per unit of force is necessarily zero. In passing to the lower frequencies a point is therefore finally reached where the response decreases appreciably. This point depends primarily upon the stiffness, s_0, of the diaphragm. A method for overcoming this loss in sensitivity at low frequencies will be discussed later.

Construction of the Microphone

A microphone was constructed very similar in design to that of the receiver just described, but with the cap omitted in order to expose the diaphragm to the action of sound waves. The dimensions of the various elements were changed so that the impedance of the diaphragm with its associated network should have a substantially constant value throughout a wide frequency range. The response as computed is shown in Fig. 8.

The moving coil microphone was calibrated experimentally by comparison with a calibrated condenser microphone. For this comparison each transmitter was mounted with its face outward in an opening in the end

wall of a cylindrical drum 30 cm. in diameter and 7 cm. deep. The two openings were spaced 180° with respect to the axis of the drum and on radii of 7.5 cm. Cracks between the microphones and the wall were carefully sealed. The wall thus formed a baffle of the same general character for each microphone. The drum was mounted on a shaft passing through its axis, about which it was rotated at a speed

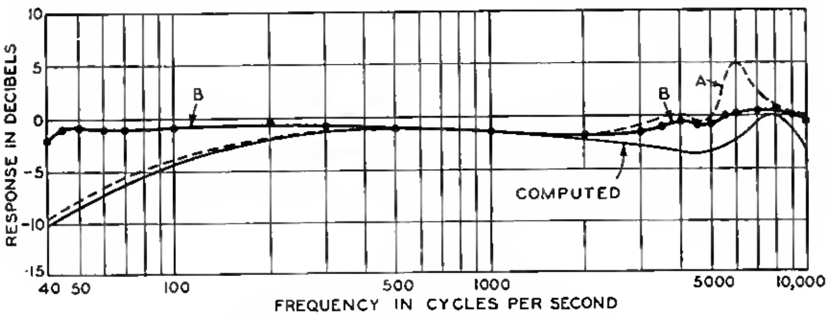


Fig. 8—Response of moving coil microphone.

of 100 r.p.m. Slip rings were provided for making electrical connections to the microphones. The drum was placed in a sound field set up by a moving coil loud speaker supplied with current from a vacuum tube oscillator. The voltage generated by each microphone was then measured with an amplifier and thermo-galvanometer. With this arrangement each microphone passed through practically the same sound field. By virtue of the symmetrical character of the drum its rotation has very little influence on any standing wave patterns in the room. A check on the reliability of the measurements was the fact that, if the position of the loud speaker was changed very little difference was observed in the ratio of the voltages generated even at the higher frequencies. Likewise, no change was observed when the electrodynamic microphone was moved a small distance axially in its mounting. The condenser microphone used in these tests had been calibrated by means of a thermophone, but a correction was made for the resonance due to the cavity over the face of the diaphragm, which is not measured in the thermophone calibration. The response of the microphone as determined in this way is shown by the curve A in Fig. 8.

The disagreement between the observed and computed values at the higher frequencies is believed to be due to resonance oscillations within the air-chamber beneath the diaphragm. In order to reduce the magnitude of these oscillations the chamber was connected through a narrow slit r_3 (Fig. 9) to a small cavity formed within the central

pole-piece. With this change in construction, the microphone was again calibrated. The results obtained in this case at the higher frequencies are shown by curve B of Fig. 8.

It is seen that the response of the microphone is quite uniform over a wide frequency range, but that it decreases at the lower frequencies. This decrease can be avoided by a reduction in the stiffness, s_0, but this

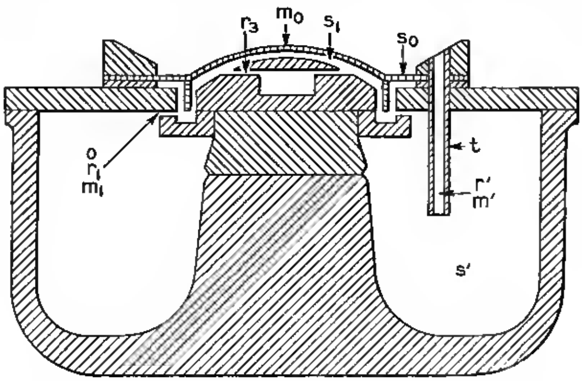


Fig. 9—Moving coil microphone.

expedient has the practical disadvantage that it makes the transmitter more delicate and increases its susceptibility to mechanical vibrations. The response at these frequencies can be increased more profitably by a simple modification which increases the force on the diaphragm under the action of sound waves. If the air-space enclosed by the magnet on the rear of the diaphragm is connected with the outside air through a tube, then, under the action of sound, a pressure will be developed within this space through the tube, differing in magnitude and phase from that of the sound outside. This pressure acts on the rear of the diaphragm. Under certain circumstances the total force on the diaphragm will be increased by virtue of this pressure.

The microphone shown in Fig. 9 is provided with a tube for performing this function. The acoustic impedance of a tube may be calculated from the formula [3]

$$Z = \frac{-\mu k^2 l}{\Pi r^2}\left[\frac{1}{1 + \dfrac{2\, J_0(kr)}{k\, J_0(kr)}}\right], \tag{2}$$

in which $k = \sqrt{j\mu/\rho\omega}$, l is the length and r the radius of the tube, μ the viscosity and ρ the density of air. At low frequencies, Z may be

[3] I. B. Crandall, "Theory of Vibrating Systems and Sound," p. 237.

represented by a resistance in series with a mass reactance, and the whole dynamical system of the microphone by the circuit diagram of Fig. 10, in which $Fe^{j\omega t}$ is the pressure in the sound wave multiplied

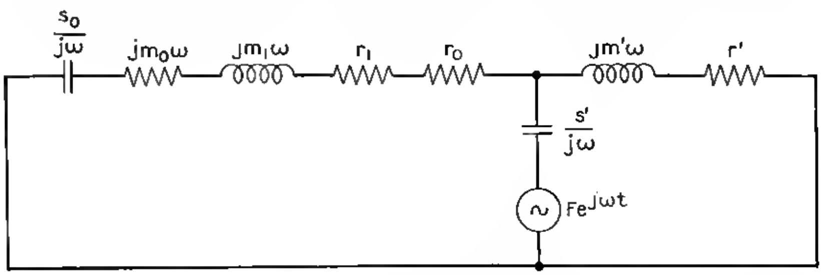


Fig. 10—Simplified circuit diagram of moving coil microphone at low frequencies.

by the effective area of the diaphragm; s', the stiffness imposed upon the diaphragm by the air enclosed within the magnet, if the tube were closed; r' and m' are the acoustic resistance and mass respectively of the tube multiplied by the square of the area of the diaphragm. The other symbols of Fig. 10 have the same significations as before.

Substituting numerical values for the various impedances of the circuit shown in Fig. 9, and solving this circuit for the velocity of the diaphragm per unit of force, we obtained the low-frequency values given by the curve B of Fig. 8. The circles give the corresponding values obtained experimentally. The agreement between these values and those computed is within the experimental errors with which the constants of the microphone were determined. The addition of this acoustic network has increased the response at the low frequencies so that there is no loss in sensitivity down to a frequency of 45 c.p.s., even with a diaphragm of comparatively high stiffness.

The absolute sensitivity of this microphone is approximately 9.5×10^{-5} volts per bar. However, in practical operation a transformer is used between the microphone and the vacuum tube of the initial stage of the amplifier. The transformer that has been used for this purpose has a voltage ratio of 100 with a variation of less than 2 db between 45 and 10,000 c.p.s. Under this condition the voltage delivered to the vacuum tube is 9.5 millivolts per bar. This value compares with approximately 3 millivolts per bar for the Western Electric Company 394 Condenser Microphone, which was designed for maximum efficiency for frequencies up to 7,000 c.p.s. The electrodynamic microphone thus has a sensitivity about 10 db higher, and covers a wider frequency range.

The condenser microphone commonly used has a cavity in front of

the diaphragm. Acoustical resonance in this cavity increases the pressure on the diaphragm, which in the case of the W. E. Co.'s 394 Transmitter may, under certain circumstances, amount to 5 db at a frequency of 3500 c.p.s. The microphone here described is believed to be relatively free from this effect, as the cavity in front of the transmitter is conical and quite shallow. The diaphragm is also smaller, so that the response is uniform over a wider angle of sound incidence.

This microphone has important practical advantages over the condenser microphone in that the amplifier may be at some distance from the microphone without loss in efficiency and in that no polarizing voltage is required. The sensitivity of this microphone is about 10 db higher. It is therefore better adapted for use in cases where the source of sound is at some distance from the microphone, since, with the smaller amplification required, mechanical and electrical disturbances, and amplifier noises in general, may be kept at a relatively lower level.